Chapter 15. RF Upgrade

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This chapter will examine the characteristics and properties of the existing Main Injector rf system with regard to its use, with appropriate modifications, at the beam intensity, acceleration rate, and longitudinal emittance specified in PD2. It will also give a brief description of a new rf system as an alternative approach.

15.1 PD2 RF Requirements

In the proposed Main Injector upgrade, six adjacent Proton Driver batches, each containing 2.5×10^{13} protons are to be injected into the Main Injector. The injected ensemble, containing 1.5×10^{14} protons, will span 504 of the h = 588 MI rf periods. Because each of the injected batches will contain fewer than 84 possible bunches, there will be a series of five small gaps in the injected ensemble. Assuming 500 filled buckets there will also be a larger gap of ~84 empty buckets in the injected ensemble. Bunches are to be injected into existing stationary buckets and each injected bunch is assumed to have longitudinal emittance (95%) ≤ 0.2 eV-s. Each bunch will contain ~3×10^{11} protons (4.8×10^{-8} Coulomb).   The average steady state dc beam current (at mean rf frequency 53 MHz), will be ~2.54 A. The mean ring circumference is 3319.419 m. The rotation period ($\beta = 1$) is 11.07 μs. With $\beta \approx 1$ the effective accelerating voltage is $V\sin\varphi_s = (240 \times 10^9)(11.07 \times 10^{-6}) = 2.66 \times 10^6$ volts /turn.

With constant acceleration rate and rf voltage, the generated phase space bucket area above transition is minimum at $\gamma = \sqrt{3}\gamma_t$. Therefore, all calculations in this section will be done at 34 GeV ($\gamma = 36.2$). The longitudinal emittance of each bunch during acceleration is not expected to exceed 0.4 eV-s. Table 15.1 shows the requirements for the high power rf system to accelerate 1.5×10^{14} protons in the 1.867 s Main Injector cycle time.

Table 15.1. Summary of RF System Requirements

Frequency	52.813 MHz – 53.104 MHz
Maximum acceleration ramp slope	240 GeV/s (initially)
Beam intensity	1.5×10^{14} protons per cycle
Beam accelerating power	5.67 MW
Number of accelerating cavities	20
Cavity R/Q	120 Ω (unloaded)
Beam acceleration power per cavity	288 kW
Total Peak Power Amplifier power required (2 tubes) (beam + cavity + plate dissipation)	~ 800 kW (includes additional cavity loading)
Maximum cavity accelerating voltage	240 kV
Total accelerating voltage available	4.70 MV

15.2 Existing MI RF System

The existing rf system consists of eighteen stations, i.e. rf cavities, power amplifiers, power supplies, and ancillary systems. A sufficient number of spare rf cavities exist to allow expansion to twenty rf stations. The rf cavities are back-to-back folded resonators with a single accelerating gap, fabricated with OFHC Copper (cf. Sec. 15.5).

Ceramic vacuum seals are located at each end of an intermediate cylinder (not shown). Each cavity is tuned over the operating frequency range, 52.75 - 53.105 MHz, by two biased ferrite tuners inductively coupled symmetrically to the opposite lower cavity outer wall (i.e. outside of the inner vacuum chamber). The tuners and their coupling loops are water-cooled, as is the entire cavity.

At present each cavity is driven by a single Eimac 4CW150000 power tetrode mounted directly on the cavity. (The tube has been renamed Y567B because of slight geometry modifications required for this installation.) An important aspect of the cavity, incorporated into the original design, is that the tube anode is tightly coupled inductively to the cavity. The coupling loop is terminated by a symmetrically located capacitance equivalent to the tube output capacitance. The terminating capacitance is located within a top-hat mounted on a flange identical to the power amplifier mounting flange. This design anticipated the possibility of replacement of the terminating capacitance with an additional power amplifier tube with minimal cavity structure modification. An added benefit of the balanced loop coupling system is that the rf voltage at the fundamental frequency is zero at the center of the coupling loop so that the dc anode voltage can be applied at that point with minimum rf by-passing requirement. An additional benefit to this geometry is that if the dc voltage is supplied through a relatively small resistance (~50 Ω), energy from non-symmetric rf modes excited in the cavity (presumably by the beam current), can be coupled to the resistance, and the Q of such modes effectively damped. This technique is presently employed in cavity operation.

The installed (and available) rf cavities, with tuners attached and power amplifier in place, have effective shunt impedance $R_s \sim 7.8 \times 10^5\ \Omega$, $R_s/Q \sim 120\ \Omega$, and $Q \sim 6500$ (at frequencies away from injection). The voltage step-up ratio from anode to gap is 12.25:1. Each cavity is designed to operate at accelerating gap voltage 240 kV. The rf voltage at each vacuum seal is approximately 80 % of the half-gap voltage, i.e. ~ 100 kV.

The cavities have higher order mode dampers attached to vacuum seal cooling fans. Originally there were additional iris-coupled mode dampers containing frequency selective ferrite at each end wall. The iris ports may still be in place, but possibly covered with copper due to water leaks in the ferrite cooling plates backing the lossy ferrite.

15.3 RF Voltage, Power, Bucket Area, and Stability

Because of the increased beam intensity and acceleration rate contained in this proposal, it appears expedient to explore the improvements in performance and stability associated with increasing the number of rf stations to twenty, and the installation of an additional power amplifier on each rf cavity. Twenty of the existing Main Injector rf cavities, each powered by two of the presently used 150 kW tetrode amplifiers, should provide the rf voltage and power required by the proposed Main Injector upgrade.

Twenty rf cavities, each delivering 288 kW rf power to the beam, will deliver the requisite 5.76 MW. The cavities, each generating 235 kV, will provide total ring voltage 4.7 MV. The accelerating voltage $V\sin\varphi_s$ at 240 GeV/s is 2.66 MV. Consequently $\sin\varphi_s = 0.566$, $\varphi_s = 34.5°$. The moving bucket factor $\alpha(\Gamma)$ (using the convention $\Gamma \equiv \sin\varphi_s$) is ~ 0.264. At $\gamma = 7.75$ the drift factor $\eta = 0.0014$. With these parameters the bucket area generated by 4.6 MV at 34 GeV is:

$$A_b = \alpha(\Gamma)\left[\frac{8R}{hc}\right]\sqrt{2E_s V/\pi h\eta} \approx 2.3 \text{ eV.s} .$$

Stability considerations will place stringent demands on the system capabilities, especially in the not uncommon circumstance where a cavity must be temporarily removed from service.

The frequency of the rf signal delivered to the rf stations is generated by a phase-lock system that locks the frequency to the beam bunch frequency. The rf voltage amplitude is controlled during acceleration by signals delivered to each station, calculated to generate the necessary power and bucket area. The phase of the rf signal is adjusted by an additional signal that makes small adjustments to correct for beam radial position errors. It is critically important that beam energy response to adjustments of the synchronous phase angle φ_s be stable and prompt. In addition to these global feedback loops, each rf station will have some element of local feedback to minimize transient and steady state beam loading effects. The gain, bandwidth, and performance of these feedback systems may be adversely affected by the physical length of the cabling necessary to implement them.

In conditions of heavy beam loading it is essential to consider the amplitude and phase of the voltage generated at each cavity gap by the rf component of beam current, in relation to that generated by the rf power generator. Because of the large bucket to bunch ratio proposed above, the relatively narrow beam bunch would have Fourier component approaching 2, so that the beam Fourier current and its image current will be near twice the steady state beam dc current. Here the beam rf current i_b is assumed to be 4.5 A.

It is convenient to represent the phase of the beam current on the positive real axis of a plot showing relative voltage and current phases. The equal and opposite image current i_i appears on the negative real axis. Also, it is common (though not absolutely necessary) to detune the rf cavity in such a way as to cause the phasor sum of the beam induced rf voltage and the rf power source voltage to be in phase with the source generator current. In this way the load presented to the amplifier is real and the anode dissipation is thereby minimized. Above transition (as is the case at 34 GeV), the cavity is tuned below its resonant frequency (so that it appears capacitive to the excitation current). This choice is consistent with one of the two Robinson stability requirements. [1,2] The rf cavity impedance presented to the generator and to the beam rf current is expressed:

$$Z_{cav} = R_{sh}\cos(\theta)e^{i\theta} \quad \text{where } \theta = \tan^{-1} 2Q\frac{\Delta\omega}{\omega_o} \quad \text{and} \quad \Delta\omega = \omega_o - \omega \quad .$$

The effective unloaded cavity shunt resistance R_{sh} is reduced by the parallel effect of additional components of real load, P_g, (exclusive of power delivered to the beam) referred effectively to the accelerating gap. The first instance of additional real load is the anode dissipation of the two amplifier tetrodes, ~280 kW. Added to the cavity dissipation, ~34 kW, the total 314 kW is larger than the 288 kW power delivered to the beam. This inequality (the requirement that the rf power source dissipation be larger than the power delivered to the beam) is in effect another of the Robinson stability criteria. The inequality is actually only a threshold for stability (see below). In order to increase the margin for beam loading stability it is proposed to deliver an additional 70 kW rf power to a water-cooled load from each operating cavity, increasing the real load at each gap to ~384 kW. The total rf power requirement per cavity becomes 672 kW, 336 kW per tube.

Using these parameters it is useful to define a resistance R_c in terms of the gap voltage V_g and the total real load P_g. A current, i_o, may be defined in terms of the resistance R_c and the gap voltage V_g. The ratio of the beam image current i_i and the defined i_o is expressed as Y.

$$R_c \equiv \frac{V_g^{\,2}}{2P_g}, \qquad i_o \equiv R_c/V_g, \quad \text{and} \qquad Y \equiv \frac{i_i}{i_o}.$$

The detuning angle required for a real load at the rf power source is Θ. The power source current necessary to deliver the required beam energy and to generate gap voltage V_g in the detuned cavity is i_g.

$$\Theta = \tan^{-1}\left(Y\cos(\varphi_s)\right) \qquad \text{and} \qquad i_g = i_o + i_i\sin(\varphi_s)\,.$$

For the conditions described here the loaded cavity R_c = 71.7 kΩ, i_o = 3.28 A. The detuning angle Θ = 48.5° and the generator current i_g = 5.83 A. The rf generator current developed by the two tubes is ~ 71.4 A. Transferred to the cavity gap by the step-up ratio 12.25, the generator current i_g at the accelerating gap is 5.1 A, slightly larger than the beam image current i_i. The cavity impedance $R_c\cos(\Theta)e^{i\Theta}$ is $47.4e^{i\Theta}$ kΩ. The gap voltage V_b developed by the beam image current i_i is 213.5 kV, and it lags the beam image current phase by the detuning angle Θ. A plot showing the relative magnitude and angular position of these voltages and currents is shown in Figure 15.1.

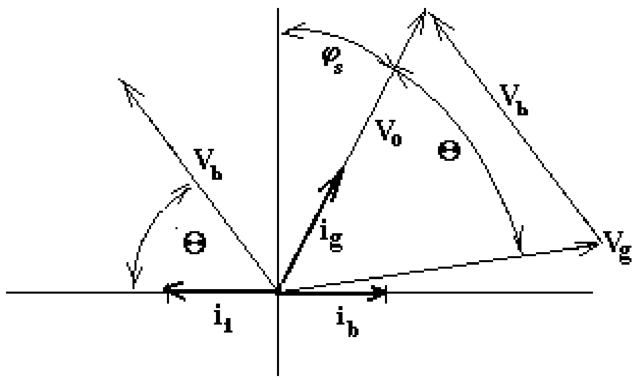

Figure 15.1. Relative phase and amplitude of gap voltages developed by the generator current i_g and the beam image current i_i. V_o is the effective resultant accelerating voltage.

The voltage phasor V_g, generated by the generator current i_g (and lagging it in phase by the detuning angle Θ), is nearly collinear with the beam current i_b. This phasor, added to the beam induced (actually decelerating) phasor V_b, creates the resultant gap voltage V_o at $(\pi/2 - \varphi_s)$. If the focusing effect of the two phasors is considered separately, and if V_b moves in phase with a beam phase error, then the primary longitudinal focusing force is generated by V_g. If the angle $(\varphi_s + \Theta)$ approaches $\pi/2$ then the beam bunches are riding at the peak of V_g, there is no longitudinal focusing force. The voltage response to a phase error ψ is (to 1st order in ψ)

$$V_g = V_o \sin\varphi_s + \psi V_o\left[\cos\varphi_s - Y\sin\Theta\cos\Theta_s\right] \quad .$$

The threshold for synchrotron phase oscillation stability under heavy beam loading is that the term in brackets cannot be negative, i.e.$Y\sin\Theta\cos\Theta/\cos\varphi_s \le 1$. For the parameters developed above, $Y\sin\Theta\cos\Theta/\cos\varphi_s = 0.826$. This is the second of the Robinson stability criteria. [2] It is related to the rf power ratio stability limit through the definitions of Y and Θ.

When the rf cavity is delivering energy to the beam the amplifier must deliver 5.83 A to the cavity gap. This translates (through the 12.25:1 transfer ratio) to 71.38 A rf current from the amplifier, or 35.7 A per tube. This current is two times the tube average dc current multiplied by the Fourier transform of the tube anode current pulse. Tube screen grid voltages are set to +1500 V dc and the control grids set to -500 V dc. Each of the grids is grounded for rf by distributed capacitance. The desired anode current pulse (circles on Figure 15.2a), is obtained by driving the cathode with a 600 volt sinusoid delivered from a low impedance transistorized amplifier. The current conduction angle is $\pm 0.22\,\pi$ radians. The curve is well matched to the dotted function

$$i(t) = 78\left[1 - \left(\frac{4.6t}{T_{rf}}\right)^2\right]^{1.3} \text{A}\,, \qquad -0.22T_{rf} \le t \le 0.22T_{rf} \quad .$$

This function allows calculation of a normalized Fourier transform, Figure 15.2b.

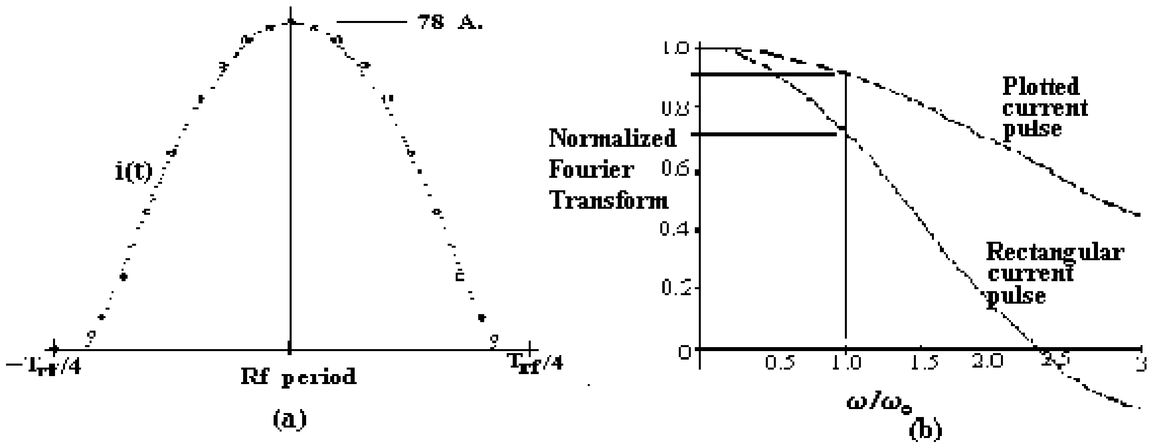

Figure 15.2. (a) Tube anode current for the grid bias and cathode drive level proposed. (b) Normalized Fourier transform for the matching calculated function (The transform of a rectangular pulse with the same area and width is shown for comparison.)

The normalized Fourier transform of the anode current pulse at the operating frequency is ~0.9. This translates to average anode current 39.6 A in each tube to develop the needed 71.4 A rf current. The anode dissipation, average tube current, and stability factor for the operating conditions proposed are:

$$\text{Anode diss.}\quad \frac{78}{2\cdot\pi}\cdot\int_{-1.3}^{1.3}\left[1-\left(\frac{x}{w}\right)^2\right]^{1.3}\left((23.-(19.2\cdot\cos(x)))+0.6\cdot\cos(x)+0.5\cdot\cos(5\cdot x)\right)dx = 139.81\ \text{kW}\ ,$$

$$\text{Average current.}\quad \frac{78}{2\cdot\pi}\cdot\int_{-1.3}^{1.3}\left[1-\left(\frac{x}{w}\right)^2\right]^{1.3}dx = 19.90\ \text{A.}\qquad \text{Stability factor.}\quad \left(\frac{Y\cdot\sin(\theta)\cdot\cos(\theta)}{\cos\left(\phi_s\right)}\right) = 0.826\ .$$

15.4 Transient Beam Loading Considerations

In the course of normal operation the cavities must operate with a 1.6 μs beam current gap and several smaller gaps on each turn. The detuning angle Θ is usually generated by a feedback system that measures the anode voltage to cathode current phase angle and adjusts the tuner bias current to represent a real anode load. Due to the tuner inductive load and limited bandwidth of the tuner bias power supply this loop is relatively slow. As a result of the passage on each turn of the beam current gap, the sensing system would send a transient to the tuning system that may result is small errors in the phase of the rf buckets just following the gaps. It may be useful to disable the tuning feedback system during the gap passage by a programmed sample-and-hold technique.

If the cavities are not re-tuned at all during the gap, the phase and amplitude of the developed rf voltage will begin to move toward V_g, the phase shift being limited by the cavity time constant. This phase shift will again cause an rf phase error for bunches arriving just after the gap. If a fast phase shifter is installed in the cathode drive system, the rf drive phase could be shifted quickly to a point leading V_o by Θ so that the phase of the rf would remain correct during the gap. This phase shifter might be part of a feedback loop around each cavity and the loop performance could be augmented by a programmed feed-forward signal. Such a system would effectively minimize longitudinal dilution of those bunches just following the gaps.

15.5 Cavity Amplifier Upgrade Considerations

Several different scenarios have been considered to meet the upgrade requirement for about 800 kW of peak rf power to each rf station. The existing power amplifier on each cavity could be replaced by just one larger amplifier capable of developing ~800 kW. This would necessitate a complete redesign of the whole top half of the present cavity. This is by no means trivial and would require extensive redesign of the rf coupling loop geometry, top half of the cavity shell, anode dc voltage feed, water cooling, and probably cavity volume changes in order to re-establish the correct resonant frequency. A preferable approach to the single amplifier scenario is discussed in Section 15.9, where a new cavity-amplifier configuration is proposed.

The configuration to be considered is the installation of a second amplifier in place of the existing cavity balancing top hat capacitor. As shown in Figure 15.3, the cavities are already flanged for a second power amplifier, eliminating the need for redesign of the entire upper half of the cavity. The second amplifier can be added by replacing the original coupling loop with a new coupling loop, as shown in Figure 15.3. The second amplifier will be identical to the first, each capable of supplying approximately 400 kW of peak rf power.

The two-amplifier approach will require fabrication of new anode dc supply modulators, located upstairs in the equipment gallery. New rf driver amplifiers capable of supplying 25 kW (peak) rf drive to the cathodes of each power amplifier will be required. Larger capacity anode power supplies will be needed in order to supply the required anode currents (~40 amps per station). Cabling will have to be added to each station to support the second power amplifier and its driver. The existing cavity tuning ferrite bias power supplies need not be changed, as their requirements remain unchanged. However, these supplies are 32 years old, and at some point they will need to be replaced with updated units in order to maintain the long-term reliability of system components.

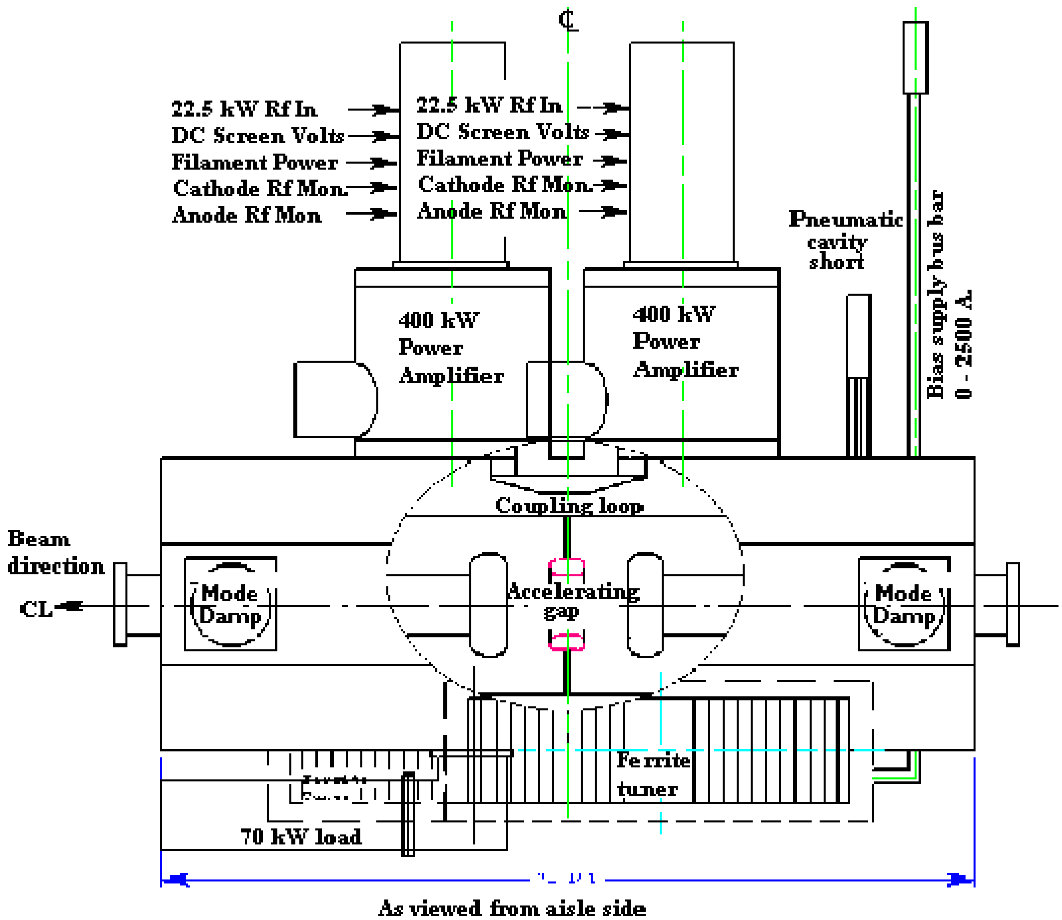

Figure 15.3. Modified Main Injector rf Cavity with two Power Amplifiers

15.5.1. Modulator requirements

A new anode voltage modulator design will be required to provide currents of 40 amperes at 21 KV to the two power amplifiers. Contained in these new modulators would be the screen, grid, and filament power supplies for the two power amplifiers along with a floating deck (electronic components operating at high voltage) and required power supplies. Because the modulator will have to supply two power amplifiers, a higher power (more plate dissipation) series tube will be used in the floating deck. This will probably result in a slightly larger cabinet, which will not be a problem in the existing equipment gallery. The present Main Injector modulators could be reused to upgrade the Booster's rf system. Another approach to a new modulator design would be to consider an IGBT.

15.5.2. Driver requirements

Because of the large rf drive power required in this configuration (25 kW per amplifier), a vacuum-tube driver will be necessary. This driver will need to be broadband and be driven by a few-hundred watt amplifier. Space in the equipment gallery is probably not a problem since it can take the place of the existing 4 kW solid-state drivers. However it would be highly desirable for these driver amplifiers to be located in the tunnel, thereby eliminating the long delay for the direct rf feedback (~ 300 ns). Minimization of cable delay is essential for maximum effectiveness of direct rf feedback This new driver amplifier will have power supplies (grid, screen, plate, and filament) located upstairs in the equipment gallery and multiple "Heliax" cables will carry the voltages from the remote power supplies to the tunnel.

15.5.3. Anode Supply requirements

Two choices are available to us. (1) Use the three existing anode supplies as they are to run three or four rf stations each. Build an additional three supplies (for a total of 6 supplies) to power the remaining stations. Since the three existing supplies are built as separate rooms off of the existing building, physical space for new supplies would have to be created. The 13.8 kV feeders that supply power to the anode supplies from the substation may require upgraded capacity. (2) Rebuild the three existing anode supplies with larger rectifier transformers capable of handling the ~6 MW peak power. This would also require upgrading the rectifier stack, capacitor bank, interphase reactor, water resistor, and possibly the fast 13.8 kV vacuum circuit breakers (step start contactors).

15.5.4. RF Controls requirements

Much of the rf controls would remain unchanged. A similar form of direct rf feedback would be employed unchanged, as in the present Main Injector system, along with transient beam loading (feedforward) compensation.

15.5.5. LCW requirements

Upgrade to the existing closed loop water systems at MI-60 that now provide LCW to the Main Injector's rf systems will be required. There are currently two systems that supply water to the rf equipment, the 95^{o} F LCW and the 90^{o} F Cavity LCW systems. Table 15.2 shows the present requirements along with the upgrade requirements.

Table 15.2. LCW Requirements

95 degree (F) LCW	Present Configuration 18 stations	Upgraded RF System 20 stations
Ferrite Bias Supply	306 gpm	340 gpm
Series Tube Modulator	630 gpm	1400 gpm
Power Amplifier # 1	630 gpm	630 gpm
Power Amplifier # 2	0	630 gpm
Driver Amplifier	180 gpm	400 gpm
Anode Supplies	105 gpm	210 gpm
2.5 MHz Coalescing	72 gpm	72 gpm
Test Station	~200 gpm	~300 gpm
Total	**2123 gpm**	**3982 gpm**
Average Heat Load (50% DF)	~3.3 MW	~7.5 MW
90 degree (F) Cavity LCW		
RF Cavity	630 gpm	1300 gpm
Test Station	~100 gpm	~200 gpm
Total	**730 gpm**	**1500 gpm**
Average Heat Load (50% DF)	~0.5MW	~2.5 MW

15.6 Main Injector RF R&D Program

In order to reach the rf power levels necessary for stable operation at the proposed beam intensity and acceleration rate, several of the innovations described should be studied on the existing cavity test stand. This will require an increase in the cathode drive rf power and the anode dc power over that which is presently available. Following such a preliminary study it would be reasonable to modify one complete existing rf station with the necessary ancillary components and to install one modified cavity in the operating Main Injector.

The first step is a simple modification a power amplifier coupling loop, so that the top-hat can be replaced by an operational Y567 tetrode (cf. 15.5 above). The screen and control grids should be properly by-passed for rf and grounded through appropriate resistance (to prevent charging), and the cathode grounded through a small resistance (large dissipation). It should then be possible to operate the cavity at normal voltage and power level with a single amplifier, the newly installed amplifier providing only loop matching reactance. The installed amplifier will be supplied with correct anode voltage through the loop, but for this test the cathode filament may remain off.

If the filament of the installed tube is heated, but no rf drive supplied to the cathode, the effect of additional anode dissipation on the rf gap voltage may be measured for various settings of the screen voltage.

Subsequently the cavity can be excited with both amplifiers at presently available cathode drive levels. Unless the amplifiers are driven at reduced levels, rf power and voltage may become excessive unless additional rf loading is installed.

For study of cavity operation with additional rf loading, it may be possible to remove one or both of the tuners and replace them with transmission lines leading to 50 Ω water cooled loads. It may be necessary to reduce the coupling loop area in order to develop the desired load power at the water-cooled loads. This test must be done, of course, at constant frequency, reasonably near the normal operating frequency. Additional coupling ports and loops of appropriate area must eventually be installed and the loaded cavity tested again for proper frequency tuning.

Spurious mode properties of the modified cavities must be studied. It may be possible to re-activate and study the end-wall iris coupled dampers, possibly with different ferrite and improved cooling.

If some method of local rf feedback is to be considered, it may be possible to study transient beam loading by using one of the newly installed power amplifiers to inject beam transients into the cavity, while using the remaining tube with feedback to study dynamic response etc. In the same vein, it is attractive to consider the possibility of assigning one of the tubes the task of generating the desired no-beam-load gap voltage, while using the other tube with feedback and/or feed-forward simply to provide the necessary beam loading compensation.

In addition to these physical measurements and observations, a more detailed analysis of the adequacy of the stability margin should be studied. This may involve beam-tracking simulations using ESME with adjusted restoring force phasors. This may also be approached analytically by expressing the restoring force fields generated by the loaded cavity as a high order polynomial in a Laplace transform variable and analyzing the location of roots as a function of input variables.

The R&D program could start immediately with one of our spare cavities and the test station at MI-60. Even though the present MI rf cavity has provisions for a second amplifier, it has never been implemented as such. Engineering effort would be needed to carry out an operating life test. A final test could be done by installing this modified cavity in the tunnel and actually accumulate running time with beam.

15.7 Summary of Modifications to Existing RF Cavities

With moderate modification to the existing Main Injector rf cavities, and extensive additions to ancillary dc and rf power sources, the Main Injector rf system can be used effectively to meet the beam intensity and repetition rates proposed in the Main Injector

Upgrade program. The number of operating rf stations must be increased from eighteen to twenty. A sufficient number of spare rf cavities exist to meet this requirement. One additional rf final amplifier tube (with enclosure shell, tube socket and other components), must be added to each cavity. The additional dc power capability will have to be provided regardless of whether the existing cavities, or redesigned cavities with lower R/Q and larger tubes, are employed.

One advantage of this proposal is that work on the cavity system upgrade can begin immediately. Improvements in the cavity design can be used to advantage either in whole or in part in continued operation of the Main Injector in its present mode. This may become especially true if the total beam load in the Main Injector is increased in the future by slip stacking or barrier stacking of the injected Booster beam.

The question of whether modified Main Injector rf systems as proposed here might be used at even higher ramp rates (up to ~300 GeV/s) will become the subject of a further and more challenging analysis.

15.8 Increased Ramp and Repetition Rate

The rf parameters outlined in Section 15.5 indicate that twenty modified Main Injector rf stations, with two power amplifiers mounted on each cavity, can develop adequate rf voltage and power to meet the MI Upgrade requirements at an acceleration ramp rate of 240 GeV/s. Amplifier and cavity parameters were shown not to have exceeded maximum allowable levels at that ramp rate. The maximum reasonable acceleration rate, with additional cavity loading and maximized cavity and tube parameters, appears to be near 300 GeV/s. There is space in the MI lattice for two additional rf cavities similar to those in use.

At 34 GeV (minimum bucket area point), a 300 GeV/s ramp rate requires accelerating ring voltage $V\sin\varphi_s = 3.32$ MV per turn. The rf beam power required to accelerate 1.5×10^{14} is 7.2 MW. With twenty-two cavities installed the accelerating voltage and power requirements per cavity are 151 kV and 327 kW.

The existing MI rf cavities can be operated at 240 kV gap voltage. With 240 kV from 22 cavities (5.28 MV total ring voltage), the synchronous phase angle φ_s becomes 39°, the moving bucket factor $\alpha(\Gamma) = 0.222$, and bucket area ~2.0 eV-s is developed.

In order to deliver the requisite 327 kW of beam power, each amplifier tube is operated at the maximum allowed anode dissipation, 150 kW. With 120 kW of additional dissipation delivered to water-cooled loads, the detuning angle Θ is 41.3°. The stability sensitive voltage phasor V_g reaches $(\Theta + \varphi_s) = 80.3°$, approaching the stability limit (cf. Figure 15.1). In this mode of operation each amplifier delivers 392 kW rf power.

The most demanding parameter in this cavity-amplifier configuration is the gap excitation current i_g, which is required to reach 6.5 A. This implies that each amplifier tube must deliver 39.8 amperes rf current, very near the maximum cathode average current limit, 20 amperes, with the Fourier transform of the anode current i(t) forced as near to unity as possible. The required drive current may be generated by driving and biasing the amplifier tube to peak current 90 A. with the smallest possible conduction angle, ~130°. This can be done by adding a third harmonic component to the cathode drive power so that the cathode is driven by relatively narrow pulses superimposed on the fundamental excitation sinusoid.

It can be concluded that with all amplifiers on twenty-two installed rf cavities operating at or near maximum gap voltage, anode current, and dissipation, the Main Injector beam intensity and repetition rate goals can be approached using existing MI rf cavities with the proposed modifications.

15.9 Proposal for a New Main Injector rf Amplifier/Cavity System

An alternative approach to extensive modification of the existing MI rf system, described above, is to design an entirely new system. This new RF system has the advantage of solving the longitudinal beam stability and transient beam loading problems by addressing them at their source, the RF cavities themselves. The beam loading voltage, ΔV, An alternative approach to extensively modifying the existing MI RF system, described in induced by the passage of a high intensity proton bunch through N, RF cavities is proportional to the number of cavities times the charge in the bunch, dq, multiplied by the cavity shunt impedance, R_{sh}, divided by the cavity Q.

$$\Delta V \propto NdqR_{sh}/Q$$

In PD2, the Main Injector bunch intensity, dq, will be increased by a factor of five over the present operating conditions. If we were to lower NR_{sh} by a factor of five, the product $NdqR_{sh}/Q$ would then remain unchanged and the transient beam loading would remain equal to that experienced today in the MI. Since the present MI RF system can accelerate and store stable beam without any fast direct feedback to the cavities, the new system running at five times the current intensity will also be stable and will not require any additional feedback loops. From a beam stability viewpoint, the two situations are identical.

The proposed new RF system keeps $NdqR_{sh}/Q$ constant by reducing the number of cavities from 20 to 14 and lowering the R_{sh}/Q of each cavity from ~100 to 25 (while keeping Q constant). This change in the number of RF cavities requires that the peak acceleration voltage of each cavity be increased by a factor of 20/14 from 235 kV to ~350 kV. The above parameters, along with the tuning range of 52.813 MHz to 53.104 MHz, completely specify the new cavity.

For specification of the power amplifier, maximum and average power requirements are needed. One of the Robinson conditions for longitudinal beam stability is that, without fast feedback, the stability limit is reached when the power being delivered to the beam equals the power being dissipated in the RF cavity and power source. From section 15.1 the total power delivered to the beam will be 5.67 MW, or 405 kW/cavity. At the stability limit each amplifier must deliver twice this value, or 810 kW/cavity. Since the amplifiers will operate in the long pulse regime with a high duty factor, the amplifier specification calls for a cw output of at least 1 MW.

A sketch of one RF cavity and amplifier that meets the above design specifications is shown in Figure 15.4. The cavity is a single gap quarter wave coaxial structure with a characteristic impedance $Z_o = 20\ \Omega$. In order to achieve a shunt impedance $R_{sh} = 100\ k\Omega$ (Q = 4000) the main body of the cavity is made from stainless steel with water cooling jackets on both the inner and outer conductors. A 15 cm diameter beam tube is connected to the 10 cm accelerating gap. The cavity body is under high vacuum with connections to the rf drive, tuner, and higher order mode (HOM) dampers through high purity alumina coaxial windows. Unlike the body of the cavity, which is intentionally designed to produce high rf losses, the tuner is designed to minimize losses. It consists of a OFHC copper coaxial line filled with 30 Transtech G-810 yttrium garnets, 32 cm OD $\times$ 12 cm ID $\times$ 1 cm thick, separated by 0.5 cm. The garnets will be perpendicularly biased above resonance to obtain a Q > 20,000. During acceleration the perpendicular bias field on the garnets will be varied from 1.3 kG to 3 kG to produce a change in μ_r from 2.5 to 1.2. The maximum energy stored in the cores is approximately 0.047 J. The maximum rf magnetic field $B_{rf} = 42$ G with an average $B_{rf} = 25$ G. The peak power dissipated in the garnets is 300 W. The tuner will be both water and forced air-cooled. The single layer solenoid, which provides the perpendicular bias field, is wound from 60 turns of 1 cm square water-cooled copper bus. The solenoid has an inductance of 650 μH and requires a current of 1000 A to 2400 A. A magnetic flux return on the solenoid (not shown in the figure) along with magnetic shielding of the beam tube will be used to reduce stray fields at the beam axis.

The power amplifier is based on the EIMAC 8973 tetrode operated in the cathode driven, grounded grid configuration. The tetrode, rated to 110 MHz, has a maximum plate dissipation of 1 MW, and may be operated as a class C RF amplifier with an output power greater than 1 MW. The tube anode is coupled through a 2000 pf vacuum high voltage capacitor to the cavity input coupling loop. The cavity step-up ratio will be equal to 15, requiring an RF voltage swing of 20 kV on the tube anode. With dc anode voltage of 20.3 kV dc, screen voltage 1100 V, and dc grid voltage –300V dc, the 8973 has delivered a measured output power of 1050 kW for a 100 s pulse at 80 MHz. Under these conditions the plate current was 78 A, plate dissipation 550 kW. The required drive power was 38 kW. For transient beam loading compensation, the 8973 can supply peak current pulses greater than 400 A and an average current of 110 A for long pulses. Commercially available IGBT modulators will be used for the HV dc plate supplies, and the present MIRF power amplifiers will be used as drivers for the 8973 tetrodes.

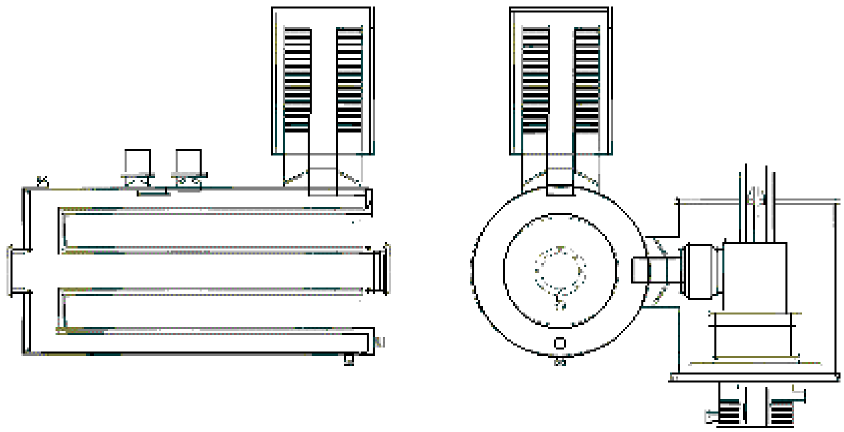

Figure 15.4. Side and end view of proposed low R/Q cavity with amplifier.

References

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